Report of the Kaons and Pions Working Group at the Fermilab Proton Driver Workshop

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Covenors Hogan Nguyen[1] and Taku Yamanaka[2]

A new 2 MW proton machine, known as the "proton driver", is being considered for Fermilab. It would play a key role in advancing accelerator−based neutrino physics. A workshop was organized in October 2004 at Fermilab to explore the physics case, as well as other physics that could be performed with this machine. We report here the summary of the pions and kaons working group on the unique physics that can be performed with the Proton Driver.

Introduction

Physics Opportunities at the Proton Driver

I−Light Meson and Baryon Spectroscopy

The topic of light meson and baryon spectroscopy is of enormous interest to the nuclear physics community because it probes the confinement and symmetry properties of QCD. The symmetry group of QCD requires the bound states to be color singlets. Beyond the meson and baryon states, QCD predicts exotic bound configurations of quarks and gluons such as hybrids (e.g. $q\underline{q}g$ and q^3g), pure gluon states (e.g. g^2 and g^3), and multiquark states ($q^2\underline{q}^2$, $q^4\underline{q}$, etc...).

Only a small fraction of these states have been observed experimentally. A goal for experimental nuclear physics is to observe the resonances, measure the partial widths, and determine the quantum numbers of these resonances through their strong decays. These are needed to compare to various theoretical ideas such as lattice gauge theory and flux tube models.

The exciting discoveries in QCD spectroscopy have been serendipitous, such as the Θ^+ pentaquark state. Although our session did not cover charm states, there have been recent surprises as well in the $D_{S0}*(2317)$, $D_{S1}(2463)$, and X(3872).

(1) Meson Spectroscopy

Beyond the meson and baryon states and their spin, radial, and orbital exitations, QCD predicts a large number of bound states of light quarks and gluons. The spectrum of $q\underline{q}$ mesons are well−known below 1.5 GeV. Above that however, they are not well−known except for higher angular momentum states.

On the other hand, the $q\underline{q}$ mesons are forbidden to have J^{PC} such as 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, and 3^{-+}. Theorists predict new types of mesons (glue balls and hybrids) to exist starting about 1.5 GeV. They can have PC quantum numbers resembling that of ordinary $q\underline{q}$ mesons, and also that of forbidden (exotic) J^{PC}. The latter signature of exotic J^{PC} allows glue balls and hybrids to be unambigously identified. The current best signal for an exotic $J^{PC} = 1^{-+}$ is the $\pi_1(1600)$ found at BNL−E852 in 1996. Follow−up experiments are planned for Hall−D at JLab. Glue balls are have been studied using lattice gauge theory[] and predicted to occur from 2 to 5 GeV. A candidate for the glueball is in the reaction $p\underline{p} \rightarrow 3\pi^0$ in the CERN LEAR experiment, where the resonance $f_0(1500) \rightarrow 2\pi^0$ was observed.

The production mechanism for these exotic states are not well understood, so it will be important to study them with as many different types of beams as possible. A nuclear physics program using pion and kaon beams at the Proton Driver will be critical to complement the electromagnetic beams of the JLab program and the e^+e^- machines.

Hadron beams have the potential to create the exotic quark and gluon bound states. However, to observe these resonances, the beam energy should be low, and the final state multiplicity should be small so that the resonances can stand out against the (combinatoric)

1 Fermi National Accelerator Lab
2 Osaka University

background.

(2) Baryon Spectroscopy

The underlying assumption in most quark models is that baryons are composed of 3 valence quarks, and the resulting spectrum is understood as exitations of these 3 quarks. The models make different predictions on the ordering and the positions of the excited states. Regardless of the model details, the number of excited states depend only the number of degrees of freedom in the baryon. However, only a fraction of the predicted states have been seen with any certainty (i.e. the "missing baryon" problem).

The only reasonably well−known excited light baryon state is the Δ(1232), whose properties are known to ~5%. Properties of a few excited state, the lowest in each partial wave, are known to 30%. Properties of other 'known' states have much larger uncertainties, therefore higher precision information is needed. The missing states must be sought in Nππ, ΛK, ΣK scattering experiments.

Here, we emphasize another aspect of the utility of the Proton Driver to the nuclear physics community. JLab is one of the two flagship facilities of the DOE office of Nuclear Physics. The N* program of Hall−B promises to deliver precision information in baryon spectroscopy using electroproduction and photoproduction. Many final states are being studied including Nπ, Nη, Nππ, Nω, Nπη, ΛK, ΣK, NKK, ΛKπ, and ΣKπ. However, because of unitarity, the amplitudes for these processes cannot be studied in isolation. The T−matrix for photoproduction necessarily includes terms for pion and kaon hadro−production. The pion and kaon hadro−production amplitudes are exactly what can be studied at the Proton Driver.

(3) Lattice Gauge Theory

It has been generally accepted that lattice gauge simulations offer the only means of calculating non−perturbative QCD. An unprecedented investment (by theory standards) has been made in this effort. It is expected that this investment will continue.

In the past, much of the lattice effort was geared towards "high energy physics", with emphasis on controlling the theoretical uncertainties in the extraction of fundamental quantities in the Stand Model (e.g. CKM matrix elements). Now, significant lattice effort is aimed at understanding non−perturbative QCD and the spectrum of states that results from it. Some key questions include building a single consistent framework for describing the spectrum and confinement (OGE, OBE, instantons, etc..?) , and understanding the failures and successes of the 'simple' quark models.

The nuclear physics community strongly endorses this line of research (via the NSAC Long Range Plan), and the funding agencies support it. For this investment to pay off, lattice calculations must be compared to high precision experimental numbers such as masses and current matrix elements. Spectroscopy experiments are essential, not only with electromagnetic beams, but especially with hadronic beams.

Ia− Beam and Detector Requirements

The beam and detector requirements for these measurements are quite modest for the Proton Driver. The nuclear physics community would use the 8 GeV proton beam with high duty cycle, as would be available from the Recycler strecher ring. For baryon spectroscopy, a secondary beam momentum of 2.5 GeV/c with π/K tagging (via a beam Cerenkov detector) is needed. This corresponds to a resonance mass of 2.37 (2.43) GeV/c^2 in the πp (Kp) system.

A secondary beam momentum spread of 5% is adequate, but the beam momentum should be measured to 1%. The beam channel should be designed to focus the beam 3−5 meters downstream from the target. This allows room for 4π detectors and shielding. Attention should be paid to keeping backgrounds low, particularly for neutral particle detectors. Polarized targets will be needed, and recoil polarization measurements will be desirable.

Current state−of−the art detectors to study elastic scattering and meson production such as CLAS at Jlab Hall−B meet the charged particle tracking requirements, but would benefit by having larger acceptance to photons. The recent program E913/914/958 with the Crystal Ball at BNL looks essentially only at neutral final states. Therefore, large solid angle (~4π) acceptance to both charged and neutrals is essential to provide complete angular distributions, and to minimize systematic uncertainties due to edge effects. Movable, small−acceptance spectrometers have their place, but not in the experiments envisioned for light−meson and baryon spectroscopy.

Gamma detection with good angular (~2°) and energy (~2% at 1 GeV) resolution is essential for measuring π^0, η, η', ω and other neutral mesons in the final state.

Ic−Conclusion

It can be argued that a typical high energy physicist does not think of QCD as being 'new physics'. But QCD is new in the sense that one still doesn't understand what QCD is doing. The motivation for studying meson and baryon spectroscopy is to probe the confinement and symmetry properties of QCD. The various models predict many interesting and exotic bound states of quarks and gluons, and only a small fraction of these resonances have been seen. The current data is either incomplete, or could benefit by having state−of−the−art detector instrumentation.

The nuclear physics community have invested heavily in a theoretical as well as experimental program to understand QCD. Understanding QCD, especially in the area of meson and baryon spectroscopy, also helps the high energy physics community as one needs to extract the interesting short−distance behavior that might be hiding in low energy phenomena.

Currently, the flagship DOE nuclear physics laboratory for spectroscopy is the electromagnetic beam facilities at JLab. However, the production mechanisms for the various QCD states are not well−understood. And so it is important to have many different types of beams. And as we have mentioned, the electromagnetic probes available at JLab, because of unitarity, cannot be analyzed without the accounting for the hadronic intermediate states. At the Proton Driver, charge pion and kaon beams would be important tools for the nuclear physics community.

The beam and detector requirements for meson and baryon spectroscopy studies are quite modest. The low energy secondary pion and kaon beams derived from the 8 GeV primary protons would be used. A high duty cycle will be desirable. We've covered only meson and baryon spectroscopy, but the Proton Driver will be an obvious draw for many other subfields of nuclear physics.

II−Pion Decays

Pions, being the lightest and simplest hadron, is an exquisite laboratory for testing fundamental symmetries. Being the lightest hadron, there are relatively few decay modes, and so the experimental signature is clean. Pion decays affect nearly every high energy physics experiment. Pion decays such as $\pi^0 \rightarrow 2\gamma$ and $\pi^0 \rightarrow ee\gamma$ are often used as the normalization mode in many branching ratio measurements, and they are frequently the limiting external systematics.

The biggest impact of pion decay physics is its role in the first−row unitarity test of the CKM matrix. The CKM parameter V_{ud} can be extracted cleanly from the decay $\pi^+ \rightarrow e^+\nu\pi^0$ (π_β). The current best V_{ud} measurement in π_β decays is V_{ud} = 0.9728(30), given by the PIBETA experiment[] at PSI. The current PDG[] average is V_{ud} = 0.9738(5), which is dominated by the measurements in super−allowed nuclear decays. However, if the experimental statistical and systematics can be improved in π_β decays, the V_{ud} extraction is ultimately theoretically cleaner than its counterpart in super−allowed nuclear decays, and in neutron and hyperon decays.

There are currently some puzzles in the form−factor of the decay $\pi^+ \rightarrow e^+\nu\gamma$. The published data set of earlier experiments such as ISTRA[] indicates deviation from a pure V−A formfactor. In PIBETA, which is a state−of−the−art detector, the quality of the V−A fit including radiative corrections is also rather poor[], with a χ^2/dof = 25.4. These poor fits would argue for additional tensor and scalar terms. There is hope that these puzzles will be resolved in the near future with analysis of additional PIBETA datasets.

It is generally agreed that the next important step in pion decay physics is to accurately measure the branching ratio of the decay $\pi^+ \rightarrow e^+\nu(\gamma)$ (π_{e2}) and normalize it to $\pi^+ \rightarrow \mu^+\nu(\gamma)$ ($\pi_{\mu 2}$). This double ratio of BR(π_{e2})/BR($\pi_{\mu 2}$) probes e−μ universality in weak charged decays. This double ratio is theoretically clean and is predicted in the Standard Model to have a value of $(1.2356 \pm 0.0001)\cdot 10^{-4}$. Beyond−the−SM scenarios typically preserve lepton universality in weak charged decays, and so it is believed to be a deeply fundamental symmetry. The current best experimental measurement[] of the double ratio is $(1.230 \pm 0.004)\cdot 10^{-4}$. In comparison with lepton universality tests in τ−decays or W−decays, the pion system's experimental precision is 3x−10x better and is unlikely to be surpassed. Increasing the experimental precision in the pion system will be extremely valuable, as the theoretical prediction current theoretical uncertainty is 40x more precise. There is significant room to discover new physics.

The π_{e2} decay is also the normalization mode to π_β. The statistical error, the internal systematic, and external systematic errors for the PIBETA[] measurement of π_β, are all comparable (0.33−0.38%). The external systematic error is dominated entirely by the uncertainty in BR(π_{e2}). Therefore, a more accurate measurement of π_{e2} is ultimately needed to improve the knowledge of V_{ud}.

There remains fundamental questions that should be pursued with pion decays. The search for the decay $\pi^0 \to \gamma\gamma\gamma$ will continue to offer the best limit for C−violation in EM. The current 90% CL experimental limit is $3.1\cdot10^{-8}$. The Standard Model branching expectation, based on parity violation in quark loops[], is ~ $10^{-31\pm6}$. Therefore, there is a large parameter space to search for new physics. New physics in the form of non−communicative QED, which adds an anomalous $\pi^0\gamma$ interaction[], can raise this branching ratio to a level of $6\cdot10^{-21}$.

Another rare decay is the QED−allowed decay mode $\pi^0 \to 4\gamma$. The 90% experimental limit is $2\cdot10^{-8}$, while the SM expectation from QED−splitting[] is $2\cdot10^{-11}$. The mode $\pi^0 \to \nu\nu$ is SM−allowed at the XX−level, while the best 90% CL limit from BNL−E787 is $8.3\cdot10^{-7}$. These decay modes, in which the SM expectations are quite small, are good opportunities to look for new physics.

The current state−of−the−art charged pion decay program is the PIBETA experiment at PSI, in which the charged pions are stopped in material. For π^0 decays, one studies them by looking at the charge−exchange reaction $\pi^- p \to \pi^0 n$. The decay−at−rest technique frees one from having to measure the parent pion kinematics, and allows for a large−acceptance apparatus that is also compact. Because of large acceptance, this technique doesn't suffer from geometrical acceptance−related systematics. However, it is believed that the decay−at−rest technique is at the systematic limit.

At the Proton Driver, we will have the opportunity to apply decay−in−flight techniques to study pion decays. The main challenge will be to build an apparatus with reasonably large acceptance. For the precision measurement of BR(π_{e2}), one also has to understand the acceptance to sufficiently high precision (10^{-3} level).

However, there are important advantages that makes the decay−in−flight technique worth pursuing. Unlike the decay−at−rest technique, there will be no target−degrader material, so this greatly reduces the beam interaction background. The decay−at−rest technique is rate−limited by the 2 μsec length of $\pi-\mu-e$ decay chain. This is a source of accidental energy deposit in the sense that a measurement such as BR(π_{e2}) has background accidental energy from a $\pi-\mu-e$ decay occuring ~ 2 μsec earlier. The pions in decay−in−flight experiment will typically have high energy, and so will allow for a more efficient rejection of the $\pi\to\mu$ decay chain. The normalization of the pion flux can be measured absolutely by a device such as a beam Cerenkov detector. Pions can also be tagged to high precision as decay products of other particles such as kaons. Finally, a decay−in−flight experiment can also measure also π^- decays. There is no decay−at−rest counterpart, since the π^- undergoes pion capture.

III−Kaon Sector

Nothing writen yet. But I have thought about this quite a bit.

Proton Economics and Sharing Beam Time

The Proton Driver and Main Injector beams need to be shared among many different experiments with very different requirements. We summarize here the key issues.

For experiments described in this document requiring secondary beams derived from the Main Injector (MI) beam, the current state−of−the−art detectors are already rate−limited. For example, the kaon experiments such as KTeV and NA48 use only a small portion of the available phase−space of the secondary beam. In 1999, the KTeV rare kaon program used a maximum of no more than $5\cdot10^{12}$ protons per 40 second pulse from the Tevatron. This is already ~3% of the planned maximum flux deliverable by the MI in the Proton Driver era. In the Proton Driver era, we expect improvement in detector technology to allow more efficient use of the beam, but it is hard to predict the rate performance of these future detectors.

In experiments that require tertiary beam derived from the MI, it is likely that more MI flux will be used. As described in the kaon section, a tertiary beam of neutral kaons could be derived from a secondary charged kaon beam. This is the ultimate method for deriving neutral kaon beams without the neutron background.

More importantly, the ultra−rare decay searches in the kaon and pion sector should be performed with a duty cycle that is as large as possible. A large duty cycle reduces the contribution from accidental energy deposits.

Achieving a large duty cycle beam from the MI is believed to be difficult for two reasons. Slow spill extraction from the MI at high intensity will introduce unacceptably large beam losses[]. And experiments in the neutrino sector will typically need fast extraction. In the mode where the MI delivers beam to both classes of experiments in a single cycle, the slow spill length will add considerably to the total cycle time. For example, the MI cycle will be 3 seconds for a 50% duty cycle, where as it will be 1.5 seconds if there is only fast extraction. Thus slow extraction will redude data−taking rate for MI neutrino experiments.

An interesting solution has been suggested to resolve the need for 120 GeV slow extraction. At the conclusion of the collider program, the Tevatron ring could be refitted with permanent magnet dipoles and turned into a 120 GeV stretcher ring. The permanet magnets allow for reduced operational cost. Also, the beam vacuum requirements are much less severe. If this can be done, then a 100% duty cycle can be achieved. The situation would be ideal for ultra rare−decay searches. A very preliminary cost estimate for refitting the Tevatron is 30 M USD[].

Experiments described herein requiring 8 GeV slow spill can use the Recyler ring. In the SC linac version of the Proton Driver, the linac can deliver beam directly to the Recyler ring, which is used to stretch out the 3 msec linac pulse. In that case, ultra−rare decays at low energy could also be performed at 100% duty cycle, with no significant extra capital cost. Currently, there are no known serious cost to the MI neutrino program.

Conclusions

We find that the Fermilab accelerator complex in the proton−driver era has the potential to offer a wide array of new opportunities that are unique to Fermilab. At the conclusion of the TeV collider program, the TeV ring can be refitted with permanent magnets, allowing for a 100% duty cycle 120 GeV stretcher ring. Similarly, the recycler can operate as an 8 GeV stretcher ring.

The 8 GeV proton beam from the Recycler stretcher ring will be extremely useful to the nuclear physics community.

Bibliography